CONTRACTION OR EXPANSION OF THE MOON'S CRUST DURING MAGMA OCEAN FREEZING? L.T. Elkins-Tanton[1] and D. Bercovici[2], [1]DTM, Carnegie Institution, 5241 Broad Branch Rd. NW, Washington DC 20015, ltelkins@ciw.edu, [2]Yale University, Dept. of Geology and Geophysics, Science Hill, New Haven CT 06511, david.bercovici@yale.edu.

Introduction: The lack of contraction features on the Moon has been used to argue that the lunar magma ocean had limited depth, or else contraction during freezing would have resulted in thrust faults and scarps, as on Mercury. We show, however, that this interpretation is incorrect for several reasons. First, production of low-density plagioclase during lunar magma ocean crystallization may lead to expansion rather than contraction. Second, a hot floating crust undergoing contraction will develop viscous folding before it develops faulting, but the time-scale for folding is so short and happens so rapidly during contraction that even these resulting features are unlikely to survive relaxation or resurfacing. Recent GRAIL gravity measurements suggest that dikes were emplaced in the lower crust, requiring expansion. Our models are consistent with that measurement and interpretation, but we demonstrate that the existence of expansion does not constrain the depth of the lunar magma ocean..

Magma ocean solidification: Since the first Apollo samples were returned in 1970, the Moon has been posited to have begun in at least a partially molten state [1, 2]. The Moon's surface, however, does not show large-scale global features created by contraction [3, 4]. Geodynamic models of lunar contraction suggest that the lunar magma ocean was constrained in depth, since freezing of a deep magma ocean would accumulate more crustal strain than is observed on the Moon (e.g., [5, 6]).

The net change in planet volume due to freezing the magma ocean is:

$$\Delta V = \frac{\rho_s - \rho_l}{\rho_l} V_l \quad ,$$

where V_l is the initial melt volume and ρ is the density of either the solid or the liquid. The accumulated surface strain, in terms of the radius of the Moon R, would then simply be

$$\frac{\Delta R}{R_0} = \frac{(\rho_s - \rho_l) V_l}{4\pi R_0^3 \rho_l} \quad .$$

The solidifying Moon is not, however, a simple bulk system that transfers its entire volumetric change directly to surface strain. The critical difference is that while crystallization of mafic phases (whose solids are usually denser than their coexisting liquid) results in contraction, crystallization of plagioclase (which is less dense than the coexisting liquid) is associated with expansion. Thus freezing of an assemblage with sufficient plagioclase will result in expansion during solidification (see also [7]), who invoke expansion during a late gabbroic melting episode). Thus, two significant modifications have to be made to the simple assessments of lunar contraction or expansion during freezing:

1. The relative densities of solid and liquid are sensitive to liquid composition, particularly TiO_2, FeO, and SiO_2 contents. Therefore, tracking the composition of the evolving magma ocean liquid and the corresponding equilibrium composition of the solidifying minerals over a number of solidification steps are critical to calculating contraction or expansion of the body.
2. The plagioclase flotation crust, in which the strains might be recorded, is not formed until after about 80% of the magma ocean is solidified. Before that point, the solids are overlain by a liquid magma layer and will not record strain.

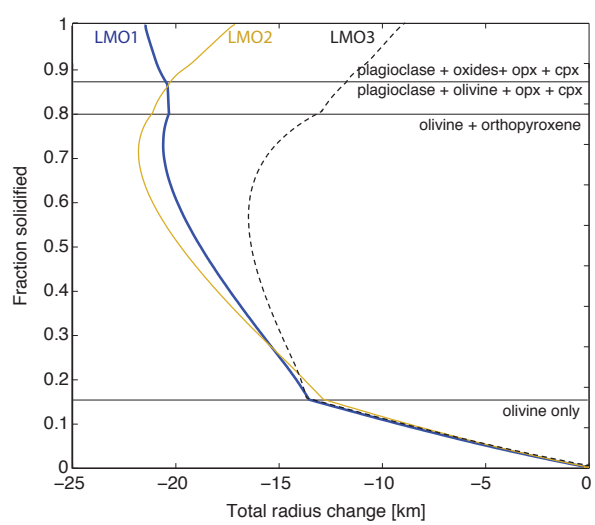

Figure 1: *Cumulative radius change with solidification for three different models. None of the change will be recorded until a competent flotation crust forms, here when the magma ocean is around 80% by volume solidified. Thus two models show ~4 km of expansion, and the other about a hundred meters of contraction.*

Results: We consider a range of potential lunar magma ocean bulk compositions, and a range of solidifying assemblages, using the methods from [8]. Our compositional models of the freezing magma ocean that indicate either contraction or expansion is possible in the flotation crust. We conclude:

1. Expansion or contraction of the solidifying Moon was sensitive to bulk composition and solidifying assemblages. Unfortunately, bulk silicate composition and solidifying assemblages are not sufficiently well known on any planet to make accurate forward predictions of expansion or contraction.
2. In some cases during the last stages of magma ocean solidification both pyroxenes and plagioclase become less dense than the coexisting liquid. The simultaneous flotation of both phases may explain the enigmatic pyroxene fraction in much of the anorthosite flotation lid on the Moon [9].
3. The plagioclase flotation crust, in which the strains might be recorded on the Moon, is not formed until after about 80% of the magma ocean is solidified. Before this crust forms, the solids are overlain by a liquid magma layer and will record no strain (Figure 1).
4. Andrews-Hanna et al. [10] suggests that intrusions in the lunar lower crust imaged with GRAIL gravity data require 0.6 to 4.9 km expansion of the Moon during crustal formation, consistent with the models presented here. Unfortunately, the amount of contraction or expansion is not a constraint on the original depth of the magma ocean, as also suggested in Andrews-Hanna et al. [10]; indeed, as demonstrated here a wide range of expansion or contraction values can be obtained for a single magma ocean depth.

Further, we derive wavelengths and timescales for the folding that would predate faulting in a contracting lunar flotation crust. This analysis shows that if the lunar crust did contract, then the folding timescale and relaxation timescale are both very short, on the order of hundreds to thousands of years, and thus any folds caused by contraction would relax away and not appear in the present day as either faults or folds.

Without the chance of recording moderate contraction in the lunar crust, gravity data such as that in Andrews-Hanna et al. [10] is the only observation available to constrain the volumetric change of the Moon during solidification. Following complete solidification, the Moon would have undergone secular cooling and further contraction, which would be superimposed on strain recorded from magma ocean solidification.

References

[1] Smith, J. V., et al. (1970) *Proceedings of the Apollo 11 Lunar Science Conference*, 1, 897-925.
[2] Wood, J. A., et al. (1970) *Proceedings of the Apollo 11 Lunar Science Conference*, 965-988.
[3] MacDonald, G. (1960) *Planetary and Space Science*, 2, 249-255.
[4] Solomon, S. C. (1986) 435-452.
[5] Solomon, S. C. and J. Chaiken (1976) *Proceedings of the Lunar Science Conference*, 7, 3229-3242.
[6] Solomon, S. C. and J. Longhi (1977) *Proceedings of the Lunar Science Conference*, 8, 583-599.
[7] Kirk, R. L. and D. J. Stevenson (1989) *Journal of Geophysical Research*, 94, 133-144.
[8] Elkins-Tanton, L. T., et al. (2011) *Earth and Planetary Science Letters*, 304, 326-336.
[9] Longhi, J. (2003) *Journal of Geophysical Research*, 108, 2-1 - 2-15.
[10] Andrews-Hanna, J., et al. (2013) *Science*, 675-678.